IAC-18,C4,7-C3.5,1,x41922

Plans and Concepts for a new generation of RTGs for Planetary Science Missions

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Abstract

Of the six types of radioisotope thermoelectric generators NASA has flown in space, only the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) is currently available for spaceflight, and it relies on technology first used for RTGs in the 1970s. The MMRTG is a rugged power system capable of delivering 110W at launch. NASA is considering future missions with higher power demands however, and sponsored a study to identify concepts and plans to address those needs.

The Director of NASA's Planetary Sciences Division was briefed on a potential enhancement to the MMRTG in late-2012, just a couple of days after the landing of the Mars Science Laboratory rover, Curiosity, on Mars. NASA subsequently funded system-level engineering and technology maturation tasks for a proposed enhanced MMRTG, or eMMRTG, in fiscal year 2013. There was no plan to build a complete generator, rather the engineering of one, and the transfer of technology from laboratories at the Jet Propulsion Laboratory to industry were begun. NASA has now formed a Project to take the eMMRTG from technology to a qualification unit. This would form the first of a new generation of RTGs in 50 years.

NASA has also formed a Project for a Next-Generation RTG concept based upon a study led by this author and a large team. NASA's Radioisotope Power Systems (RPS) Program set the objective for the study to explore what possible options NASA has for Next-Generation-RTGs. The scope and breadth of the study included many possible destinations within the solar system, and traded a variety of RTG conceptual designs, and risk rated a variety of thermoelectric materials and couple configurations. Requirements were defined for the RTG concepts, a variety of thermoelectric materials were evaluated to find the most mature candidates, and performance was estimated for each RTG concept that could use the most mature of these new thermoelectric materials.

The study relied upon mission concepts outlined in the latest Planetary Science Decadal Survey (2011), other more recent mission studies completed throughout the agency, and recent analyses of potential missions to ocean worlds to identify requirements that were not applied to previous RTGs but might prove valuable to these NG-RTGs.

RTG concepts with maximal potential utility were identified as being modular and ranging in power output from 50 to 500W. A variety of RTG design concepts with several distinguishing characteristics were formulated.

The plans and concepts for a new generation of RTGs (the eMMRTG and NG-RTG) will be discussed.

Keywords: radioisotope, thermoelectric, RTG, RPS, next-generation, deep space

Acronyms/Abbreviations

APL = Applied Physics Laboratory
AR = Aerojet Rocketdyne
BOL = Beginning of Life
CONOPS = Concept of Operations
DOE = Department of Energy
EDL = Entry, Descent, and Landing
eMMRTG = enhanced Multi-Mission Radioisotope Thermoelectric Generator
EODL = End-of-Design Life
GPHS = General-Purpose Heat Source
GPHS-RTG = General Purpose Heat Source Radioisotope Thermoelectric Generator
GRC = Glenn Research Center
GSFC = Goddard Spaceflight Center
INL = Idaho National Laboratory
JPL = Jet Propulsion Laboratory
LPPM = Lifetime Performance Prediction Model
MMRTG = Multi-Mission Radioisotope Thermoelectric Generator
NG-RTG = Next-Generation Radioisotope Thermoelectric Generator
QU = Qualification Unit
RPS = Radioisotope Power Systems
RPSP = Radioisotope Power Systems Program
RTG = Radioisotope Thermoelectric Generator
SMT = Surrogate Mission Team
SRD = Systems Requirements Document
TAPP = TESI Advanced Power Predictor
TESI = Teledyne Energy Systems, Inc.

1. Introduction

RTGs were invented in 1954 by scientists at the Mound Laboratories in the USA working under contract with the US Atomic Energy Commission, precursor to the US Department of Energy (DOE). NASA saw the advantage of RTGs and began flying them in 1968 on the Nimbus meteorological satellites.

Several varieties of RTGs have been flown by NASA since then, but all of them used one of two thermoelectric systems. The very earliest NASA missions, such as the Pioneer missions, and subsequently, missions bound for planets with atmospheres (Mars, for example) used PbTeTAGS couples sealed in a pressurized cannister. PbTeTAGS is shorthand for the chemical makeup of segments of the thermoelectric couple and stands for Pb-lead, Te-Tellerium, TAGS-Tellierium-Gold-Germanium-Antimony. Generators to be used solely in vacuum in deep-space relied on couples built from SiGe. SiGe is shorthand for Silicon-Germanium.

The MMRTG is the only RTG available to NASA for use today. It uses the PbTeTAGS materials found in RTGs used for the Viking missions in the 1970s. NASA's director of the Planetary Sciences Division was briefed on a potential enhancement to the MMRTG in 2012, just a couple of days after the landing of the Mars Science Laboratory rover, Curiosity, on Mars. Subsequently, NASA funded the engineering of the proposed enhanced MMRTG or eMMRTG. The eMMRTG design introduces the first new thermoelectric materials and technologies for RTGs in 50 years. However, this approach did not include concrete plans to build generators for qualification or flight.

While the eMMRTG is a member of the set of new generation RTGs, NASA recognized that it is not powerful enough for many deep-space science missions and commissioned a study to identify potential, supplemental RTGs. This study was formally named the Next-Generation RTG Study. The study was completed in June, 2017 [1, 2]. The mission analysis supporting the study examined 100s of missions flown and documented [3] to arrive at requirements for a Next-Generation RTG.

Since that time, NASA has formed Projects for the fabrication of a proposed eMMRTG and a conceptual Next-Generation RTG, or NG-RTG, for qualification testing. The reorganization of the RPS Program is depicted in Figure 1. Level II represents the RPS Program Office. Level III represents the projects and the Fundamental Research task.

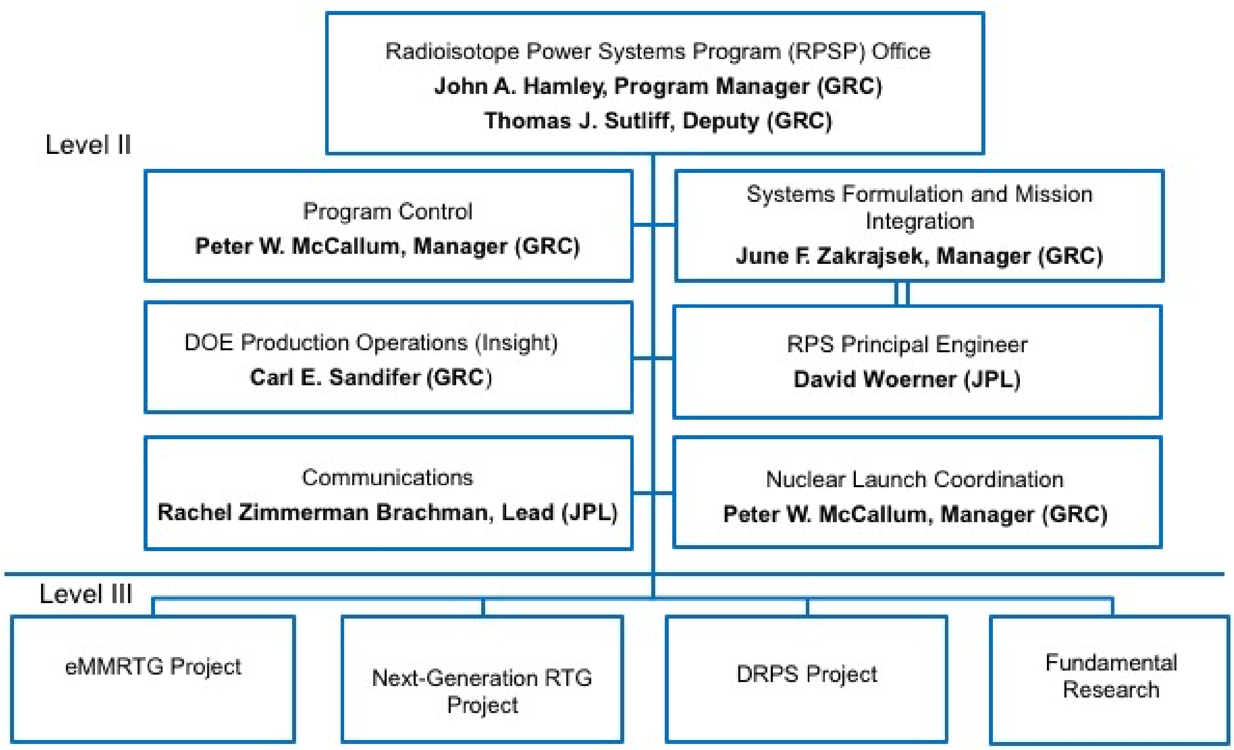

Figure 1. The Organization of the RPS Program and the RPS Projects.

The remainder of this paper will discuss the eMMRTG and NG-RTG concepts and the Projects and their plans.

2. The Proposed eMMRTG

The eMMRTG development is in its fifth year and is transitioning from the tasks of systems engineering and technology maturation into a NASA Project to develop a qualification unit with the US Department of Energy. The eMMRTG is an enhancement of the MMRTG and replaces the thermoelectric couples, enhances the bulk insulation in the modules, and applies a finish to the heat source cavity to allow for a higher operating temperature. Should NASA decide to proceed with the eMMRTG, the unit would look identical to the MMRTG from the outside, fit in the same envelope, and weigh nearly the same. Only the few changes highlighted in Figure 2 would need to be made [4].

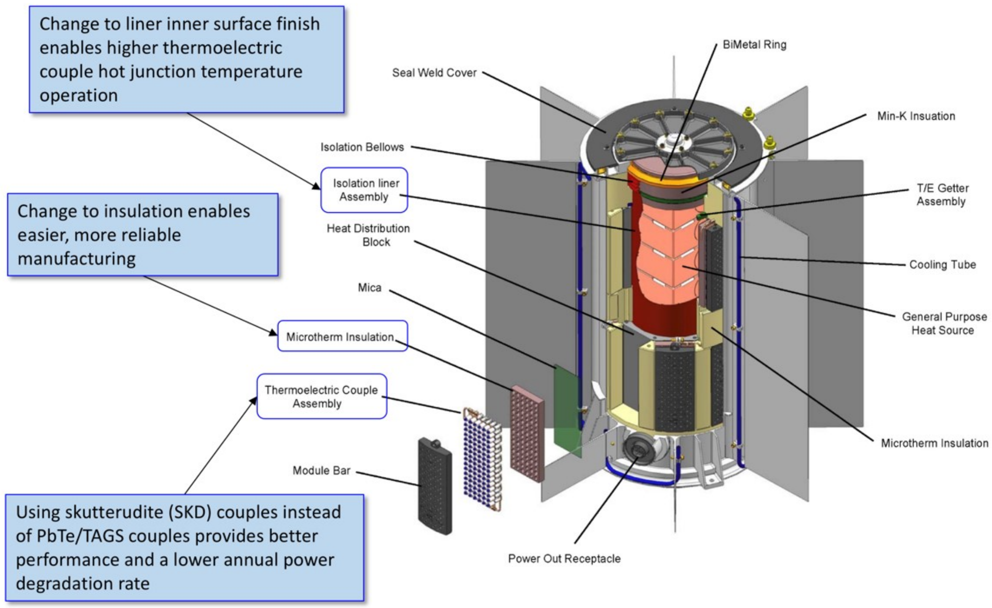

Figure 2. Enhancing the MMRTG comes about by changing the circled items.

The new thermoelectric couples being designed into the eMMRTG are composed of skutterudite (SKD), a compound that operates near 600 degrees C and is estimated to produce 50% more power at the EODL of the eMMRTG, or 17 years. Figure 3 shows the MMRTG and eMMRTG thermoelectric couples side-by-side.

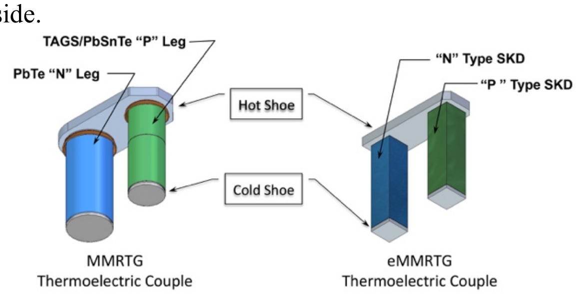

Figure 3. Two examples of thermoelectric couples: the MMRTG thermoelectric couple (left) and the skutterudite (SKD) couple (right).

Teledyne Energy Systems, Incorporated (TESI) of Hunt Valley, MD, and Aerojet Rocketdyne are working with NASA's Jet Propulsion Laboratory and Glenn Research Center to evaluate and mitigate risks, fabricate and test thermoelectric couples, refine manufacturing processes, and verify power estimation tools.

The eMMRTG Project is carrying a requirement to produce a minimum of 77W at EODL. This is ~50% better than the MMRTG is estimated to produce at EODL.

The Project is planning its second "Gate" review in January 2019. This is a review of the eMMRTG Project, its accomplishments, plans, and risks. A Review Board (RB) will be chartered by the Department of Energy's Space Radioisotope Power Systems Program Manager and the NASA RPS Systems Formulation and Mission Integration (SF&MI) Manager. The RB will provide an expert assessment of the technical approach and results, risk posture, and progress against the baseline plan. The decisions to act on the assessments are at the discretion of the Government.

Following a successful "Gate 2 Review," the Project would fabricate thermoelectric couple modules containing 48 couples and put those on life test. In addition, the DOE's Idaho National laboratory (INL), would issue an RFP for the remaining work for the eMMRTG. This would include all remaining reviews such as a Gate 3 review, Preliminary Design Review, and a Final Design Review. The contract would include the option to fabricate and test a qualification unit of the eMMRTG after a successful Gate 3 review, and options to build flight units following successful qualification testing of an eMMRTG qualification unit (QU). The goal is to complete the qualification testing in 2024.

2.1 eMMRTG Technologies

The eMMRTG technologies are the thermoelectric couples, their insulation, and a finish on the heat source cavity. Transfer of the formulation of the thermoelectric materials and fabrication process is complete. Teledyne Energy Systems, Inc. can now make skutterudite thermoelectric materials, dice them, and has defined quality assurance measures for those processes, and is scaling up to produce them at a rate consistent with producing an RTG in ~1 year. The most significant remaining work on the couples is related to the interface materials between the skutterudite and the interconnects, and the bulk of this work entails long-term testing which is beginning near the end of September 2018.

The insulation evaluation process has been finalized. A bulk, fibrous insulation called Promolight® was used in the MMRTG. That is being replaced by the same bulk insulation impregnated with aerogel. The process and developmental tests of this invention are now complete. This new insulation would speed the manufacturing process, remove a great deal of "touch labor," and minimize heat loss around the couples.

The finish on the heat source cavity surface was designed, tested, and independently verified. The process for producing this finish and the underlying parts has been documented for use when the QU fabrication is begun. The finish raises the temperature of that surface by ~70 degrees Celsius so that the thermoelectric couples have a hot side temperature of 600°C.

2.2 eMMRTG Systems Engineering

eMMRTG Systems Engineering task began in 2013 and is now focused solely on risk reduction. That is, all required design changes have been identified, analysed, and accepted or rejected. What remains is to reduce the risks to successful operation of this RTG in flight.

The significant system risk reduction activities are to finalize and peer review the TESI thermal and power modelling tool called the TESI Advanced Power Predictor (TAPP), conduct Monte Carlo analyses of the eMMRTG temperatures, and complete long-term testing of another bulk insulation called Min-K®.

TAPP predictions will be compared with the JPL Lifetime Performance Prediction Model (LPPM) to highlight errors, guide refinements, and develop confidence in the TAPP and this will be followed by a peer review so Subject-Matter Experts (SMEs) can scrutinize the algorithms and verification methods used to mature the TAPP software.

Monte Carlo analyses of the eMMRTG temperatures will be conducted subsequently to ensure that the temperature requirements and hardware components have margins. This was completed previously with an earlier version of TAPP and few thermal issues were found. This will be repeated with a more refined version of TAPP to verify that nothing was missed in the initial Monte Carlo runs.

The eMMRTG heat source cavity would operate at approximately 70 degrees Celsius higher than the MMRTG. The insulation that supports the heat source stack must support the stack during launch and post-launch events such as Entry, Descent, and Landing (EDL) on Mars. There is no indication the insulation cannot be operated at a higher temperature but the margin on supporting an EDL has been reduced. Consequently, a test campaign was started to test the insulation at higher temperatures and in a slightly modified configuration to raise the margin; this work will be completed in mid-2019.

2.1 The eMMRTG Project Plans

While JPL has issued the contracts for the eMMRTG for the last five years, the DOE would issue the contract after the Gate 2 review. This is due to the transition from technology maturation to an eMMRTG Project. Aerojet Rocketdyne would be the prime and TESI the sub on a contract issued by DOE INL and funded by NASA. TESI would be the technology provider, and Aerojet Rocketdyne (AR), the systems integrating contractor. The current schedule is sparse because AR is not yet on contract. The schedule is as shown in Table 1.

Table 1. The notional eMMRTG schedule as held by the eMMRTG Project

PROJECT MILESTONE	PLANNED DATE
Gate 2 Milestone Review	1/11/19
Contract Award	2/1/19
Testing of 48 couple Modules initiated (Beginning of Life Power Reading)	2/2019
MMLT-7 On-Test (Beginning of Life Power reading)	Per contract schedule
LPPM Prediction Iteration 1	Per contract schedule
6 Month Sublimation Test Destructive Physical Analysis (DPA) Complete	Per contract schedule
12 Month Sublimation Test Destructive Physical Analysis (DPA) Complete	Per contract schedule
LPPM Gate 3 Life Prediction	Per contract schedule
Gate 3 Milestone Review	9/16/19
Award Option II – EMMRTG Qual Unit development	12/16/19

NASA's Radioisotope Power Systems Program has stipulated that the eMMRTG QU shall be complete by 2024. This provides the Project with several years to complete that unit and test it. A notional schedule shows this in Figure 4. It is notional as no subcontractor has been selected yet. The Project is finalizing the RFP for a procurement from a subcontractor.

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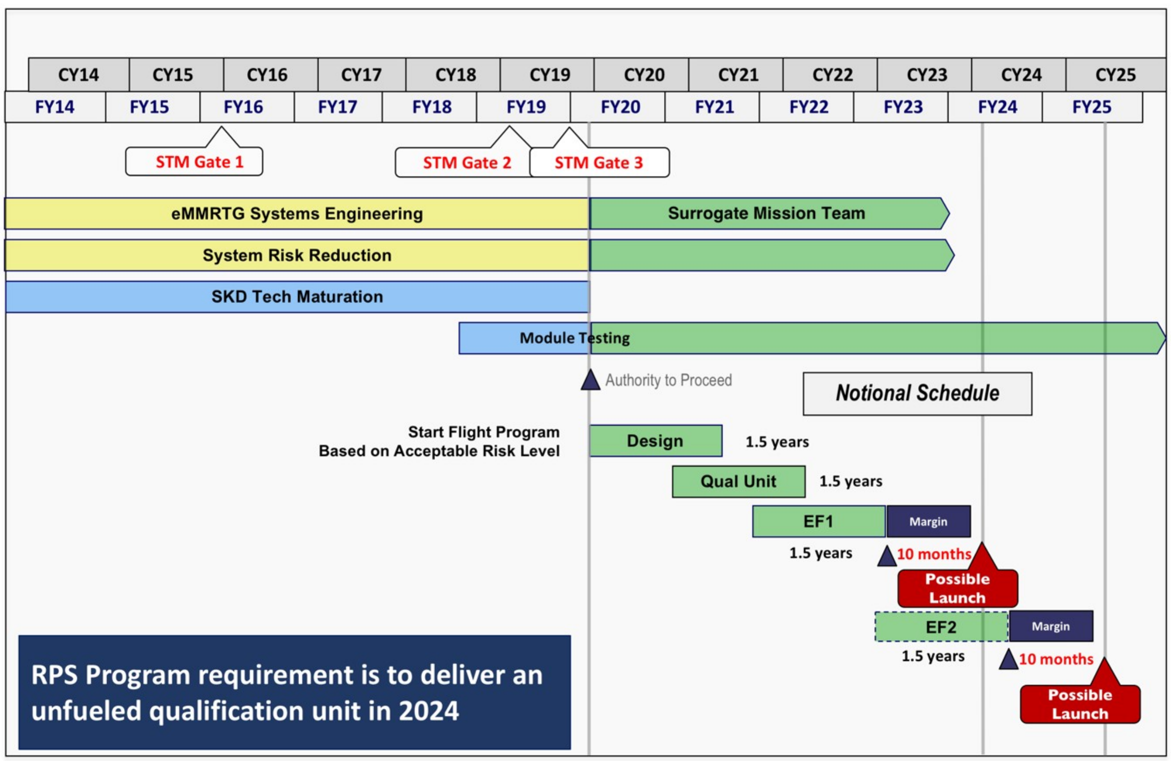


Figure 4. A notional schedule for the development of the eMMRTG. The schedule will remain notional until the eMMRTG Project has selected a subcontractor to build the eMMRTG qualification unit. Further, the flight units, depicted as EF1 and EF2, are options.

3. The Next-Generation RTG Project

The Next-Generation RTG (NG-RTG) Study completed in June of 2017 advised NASA of the need for a vacuum-rated and modular RTG. NASA subsequently implemented a Project to produce a vacuum-rated qualification unit (QU) RTG currently called "Next-Gen RTG". The purpose of the NG-RTG Project is to define and develop the RTG technologies, and then to design a vacuum rated QU using those technologies.

The Next-Generation RTG Project is quite different from the eMMRTG Project. It poses a much more challenging endeavour. There is no RTG to enhance. The design will be produced nearly from scratch but likely borrow design features and inspiration from flown RTGs such as the GPHS-RTG [5]. The design of the NG-RTG is constrained by two hard constraints: it must use the GPHS Step-2 and fit within the DOE's shipping container. The GPHS Step-2 is the only space-qualified heat source for Radioisotope Power Systems (RPS) presently available; it houses a sufficient quantity of plutonium oxide fuel to heat an RTG. The DOE's shipping container is the 9904 cask.

Ultimately, a complete Systems Requirement Document (SRD) will be written by NASA to fully define the NG-RTG requirements. The first version of this document will be published in October 2019. The development of this document will be aided by extensive trade studies to be conducted by the Surrogate Mission Team (SMT); the SMT is comprised of engineers from NASA GRC, JPL, and GSFC, the DOE, and APL. The trades will include exploring and defining the level of modularity required, what should be the design point for peak power for these RTGs, what should be the design life of these RTGs, and how and where should the unit be fueled. Requirements would flow from these trades into the SRD. Additional requirements will flow from a Concept of Operations (CONOPS) that defines how the Next-Gen RTG would be used once it is delivered to NASA by the DOE INL.

In addition, the NG-RTG Project will be conducting trades as well that will inform the SRD. This top-down and bottom-up approach of requirements development should lead to a coherent and consistent set of requirements that a subcontractor can use to define lower-level requirements and, ultimately, build an NG-RTG QU by 2028.

3.1 NG-RTG Technologies

It is anticipated that the NG-RTG requires several technologies to be developed. The thermoelectric conversion materials, their configuration, the insulation around the materials, and potentially others would need to be developed and matured before it becomes possible to complete an NG-RTG. NASA has funded research into thermoelectric materials at JPL for the last two decades and continues to fund that work. The NG-RTG Study scoured literature and other sources of information on thermoelectric materials to cull a list of materials that could be used in an NG-RTG. JPL continues work on a small number of materials that show promise. Those are rapidly being configured and tested for potential use in the NG-RTG. The intent of this work is to produce test results that can be documented in a "databook" that describes the characteristics of the materials in great enough detail that a subcontractor can develop plans to produce the materials in sufficient quantities to make NG-RTGs all while the subcontractor designs and builds the NG-RTG.

NASA posted a set of NG-RTG requirements in a Sources Sought Notice [6]. Some of the significant goals and requirements posted were:

- The NG-RTG shall be modular, as depicted in Figure 5
- Power output of the largest variant: up to 500W.
- Internal device Hot junction temperature: less than 1100°C
- Sink temperature: -269°C
- Fuelled System Mass: less than 60kg
- Design life: 17 years
- Allowable Flight Envelopes:
  - Voltage: 22-34 VDC
  - Flight Fin Root Temperature: 50-200°C
- Primary Modal Frequency: greater than 50 Hz

In addition to the technologies being developed at JPL, NASA is open to flying technologies developed by the subcontractors, and all potential technologies will be reviewed during an initial conceptual studies phase. The most important requirement for the Next Gen RTG Project is the design and build of a vacuum rated QU by 2028.

3.2 Systems Engineering

The NG-RTG technologies cannot be developed independent of a system concept. The thermoelectric materials must be tested in relevant environments for example. This includes their thermal, launch, atmospheric, radiation, and storage environments, and many more. The NG-RTG Project and RPS Program includes systems engineers to bind these environments so that meaningful tests can be performed on the NG-RTG technologies.

The systems engineers provide context for the maturation of the NG-RTG technologies while also providing SMEs that will aid NASA in where NASA needs deep-expertise about RTGs and NG-RTG concepts.

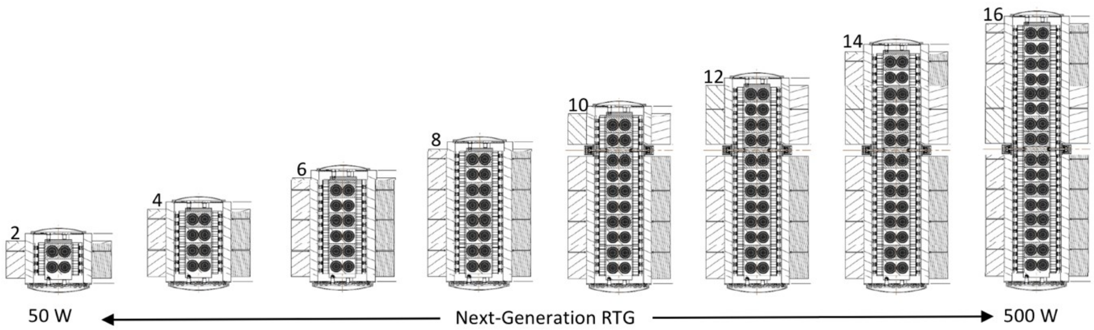


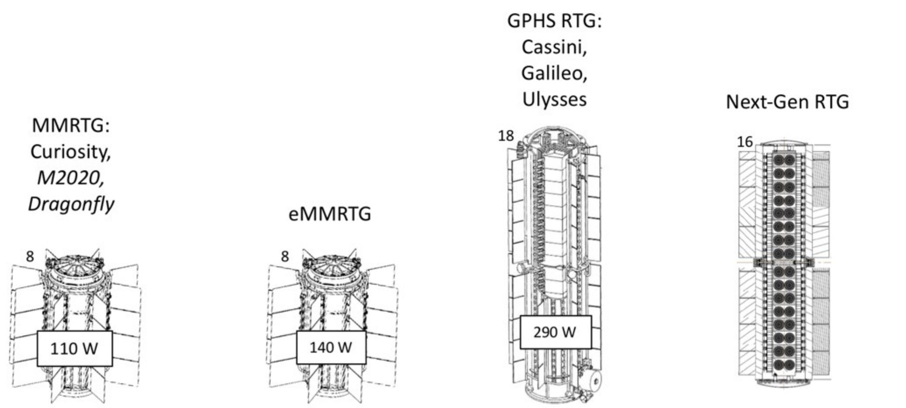
Figure 5. Next-Generation RTG concepts in cutaway view. The number at the upper end of each depicted RTG is the number of GPHS Step-2s used to heat that RTG. The largest variant of the NG-RTG uses 16 GPHS Step-2s.

3.3 The Next-Generation RTG Project Plans

The Next-Generation Project has been created to deliver an unfuelled qualification unit by 2028. Similar to the eMMRTG, the RPS Program has selected the date and the NG-RTG Project is working to achieve that. The Project office has selected systems engineers and is funding further technology development at JPL, and issued a Sources Sought Notice to industry, and had a technical interchange meeting with potential subcontractors. The responses to the Sources Sought Notice have been received and are under review. The Project will use the information gleaned from the responses to aid in the development of an RFP to take potential Next Gen RTG technologies from a system concept phase, through a technology maturation phase, and then development of the unfuelled vacuum rated QU. The technologies used for the system concepts could be based upon the technology that NASA has invested in at JPL or the subcontractors could propose their own technology.

4. Conclusions

The MMRTG powering the Curiosity rover on Mars is now just a few weeks from its 10th year of operation. NASA is in its fifth year of technology maturation for the proposed enhanced MMRTG. The Next-Generation RTG Project is well on its way to developing a conceptual RTG that could produce almost twice the power of the last "large RTG," the GPHS-RTG. Figure 6 provides a table that allows comparisons of the MMRTG, eMMRTG, GPHS-RTG, and NG-RTG.



Power, launch, W	110	140	290	400-500
Efficiency, BOL	5.5%	7.5%	6.4%	10-12.5%
Power, EODL, W	55	91	213	308-385
Degradation rate, av	4.8%	2.5%	1.9%	1.9%
# GPHSs	8	8	18	16
Length, m	0.69	0.69	1.14	1.04
Mass, kg	45	44	57	62

Figure 6. RTGs for comparison. Note the MMRTG is on the Curiosity rover, will fly on the Mars 2020 rover, and could fly the proposed Titan helicopter, Dragonfly. The GPHS-RTG was flown on the Cassini, Galileo, and Ulysses missions.

NASA has just celebrated its 60th anniversary, and a new generation of RTGs has the potential to power some of NASA's next deep space missions for several decades. The eMMRTG and NG-RTG Projects are slated to deliver a new generation of RTGs in the next decade.

Acknowledgements
The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. This work was performed by a large team that drew on skills and expertise within and external to NASA. This author, however, would like to acknowledge the professional and knowledgeable support provided by the participating organizations: NASA's Glenn Research Center, Goddard Space Flight Center, and Jet Propulsion Laboratory, the John Hopkins University's Applied Physics Laboratory, the US Department of Energy's Idaho National Laboratory, and the University of Dayton Research Institute.

The information in this paper is pre-decisional and is provided for planning and discussion only.

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